

Ocean-Clutter Model For High-Frequency Radar

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Abstract—High-frequency (HF) radar has been established as a remote sensor in the ocean environment. One of the characteristics of returns from this radar is a high level of ocean clutter. The clutter signal hampers target detection; however, it is useful for estimating ocean conditions. The generally accepted ocean-clutter models are based on electromagnetic scattering from the ocean waves, and the modeled Doppler spectrum consists of two components: A narrowband component is due to first-order "Bragg" scattering, and a broadband component is produced by second-order effects from two sets of ocean waves.

Motivated by the objective of clutter suppression for target detection, this paper investigates the time-varying behavior of ocean-clutter signals. The results suggest that the ocean clutter consists of only two narrowband signals, with time-varying frequencies. The spectrum of this angle-modulated signal model agrees closely with the observed clutter spectrum.

Processing of HF radar data demonstrates that low-order, time-varying prediction filters can be used to model the ocean-clutter signal and significantly enhance target-to-clutter signal ratios. It is also postulated that the time variations of the narrow-band clutter signals are related to the ocean wave-height spectrum; initial results are encouraging, and this could lead to a robust method for estimating the sea state using HF radar.

Keywords—High-frequency radar, ocean clutter, target detection, adaptive filtering.

I. INTRODUCTION

IF the ocean surface is illuminated by high-frequency (HF) electromagnetic waves, then significant energy, at well-defined frequencies shifted from the transmitted frequency, can be detected. Crombie [1] first observed this effect and attributed the dominant component of returned energy to back-scattering from ocean waves having a wavelength half that of the radar wavelength. Two sets of such ocean waves, moving radially to and away from the radar site, respectively, behave as diffraction gratings and cause constructive interference of the scattering returns. These scattering returns exhibit two distinct Doppler frequencies corresponding to the characteristic velocity of propagation of the two sets of ocean waves. Fig. 1 shows these two "Bragg" scattering frequencies for an HF radar operating at 24.5 MHz; at this frequency the Bragg scattering is due to ocean gravity waves of about $5.9 = \lambda$ wavelength. The characteristic propagation speed of about 3.04 m/s of these "Bragg" waves translates to a Doppler frequency of ± 0.51 Hz. Any surface current component along the propagation direction modifies the wave velocity with a corresponding change in the Bragg-Doppler frequency. This selective interaction of electromagnetic waves with the ocean waves and current led to numerous implementations of HF radars for the remote sensing of the ocean conditions (see, for example, [2]).

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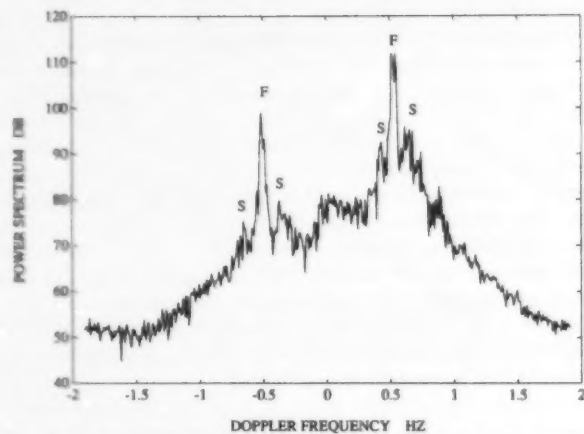


Fig. 1. Typical HF radar power spectrum showing the characteristic first-order (F) and second-order (S) scattering peaks.

In addition to the dominant Bragg-scattering returns, a smaller and more complicated feature of the HF radar Doppler spectrum is referred to as the "second-order" scattering. As the name implies, this portion of the Doppler spectrum has been modeled as double scattering from two ocean wave components, which match half the radar wavelength after vector addition along the radar beam direction [3], [4]. Hasselmann [5] proposed a simpler model, suggesting that the second-order "side-bands" are replicas of the ocean wave-height, nondirectional temporal spectrum, but no conclusive evidence was published.

The inverse problem of extracting the ocean wave-length spectrum from the clutter signal involves inverting a nonlinear integral equation; some successful proposals have been reported [6], [7]. Inversion techniques are susceptible to noise, and the author is not aware of any system for the routine estimation of the sea state from HF radar data. The strong ocean-clutter signal has also limited the application of HF radar for target detection [8]; this is particularly true for vessel detection, where the expected Doppler radar frequency frequently falls within the clutter Doppler spectrum.

We are interested in characterizing ocean-clutter signals with a view towards exploiting the over-the-horizon target-detection capabilities of HF radar. In an earlier publication [9], we reported that the dominant Bragg ocean-clutter signal exhibits some time-varying characteristics. This paper describes a detailed investigation of the time-varying behavior of the ocean clutter and shows that the ocean-clutter can be modeled by two narrowband signals, with time-varying frequencies, centered around the two Bragg frequencies. The time variation of the two narrowband clutter signals can be interpreted as two independent angle modulations. It is demonstrated that the spectrum of such an angle-modulated signal agrees closely with the spectrum of HF radar data and accounts for the characteristics corresponding to both the well-known first- and second-order scattering peaks.

This time-varying model for the ocean-clutter signal can have a significant impact on the processing of HF radar data. As an example, it is shown that a low-order adaptive prediction filter may be used to track and subsequently suppress a major portion of the time-varying ocean-clutter signal. The demonstrated increase in the target-signal-to-clutter ratio will enhance the detection performance of HF radar.

It is postulated that the observed angle-modulated clutter-signal results from the spatial wobbling of the Bragg ocean waves. In other words, it is suggested that the ocean gravity waves, corresponding to the Bragg-scattering returns, are not moving with a uniform velocity. The average velocity may be accurately determined using oceanographic models, but the instantaneous velocity is continuously changing, since this wave interacts with the other ocean waves. Thus the frequency variations may be directly related to the ocean wave-height spectrum. This alternate interpretation of the ocean clutter behavior may lead to a more robust method for estimating the sea state from HF radar data. Positive initial results are presented and further work is underway to process data under more controlled conditions with collaborating wave-buoy measurements.

II. BACKGROUND

Using different approaches, Barrick [3] and Walsh [4] have derived similar analytical expressions for the ocean-clutter radar cross section in the HF band. This cross section, evaluated as a function of the radar Doppler frequency, contains the first- and second-order scattering components and is related to the directional ocean wave-height spectrum. The impact of ocean clutter on target detection may be appreciated by the fact that the first-order clutter cross section, from Bragg ocean waves traveling with the wind, is typically much stronger than the cross section of a ship target. A ship target thus cannot be detected if it is moving with a velocity close to that of the Bragg waves, so that Doppler-frequency discrimination is not possible. Depending on the size of the ship and the sea state, even the second-order clutter cross section can mask the target. These concerns were addressed by Maresca and Barnum [8], who investigated the feasibility of detecting ships with HF radar. Their results stated, in essence, that the ocean clutter would limit target detection in significant portions of the Doppler spectrum. The resulting extent of a target blind speeds would thus make such a radar device impractical.

If HF radar is to be used for low Doppler target detection, then some characteristic differences, other than Doppler frequency, between the clutter and target signals must be established. These characteristic differences could then be utilized to effect a separation of target signals from the ocean clutter signals; this would decrease or even eliminate the blind speed ranges. Towards this end, we started an investigation into the time-domain characteristics of HF radar signals.

In the time domain, the signal amplitude of HF radar, pointed at the ocean, has been observed to exhibit a fluctuation characteristic with a distinctive pattern of strong amplitudes separated by periods of fading. Fig. 2 shows the amplitude of a typical HF radar run collected from a range cell at a distance of 11.4 km, containing ocean returns only. Such data was initially analyzed to determine the time-varying characteristics of the two dominant Bragg-frequency components [9]. This analysis assumed the frequencies of these Bragg components to be constant, and a complex demodulation scheme was employed to study their time-varying magnitude and phase behavior. The result of the analysis was that these Bragg components were exhibiting a

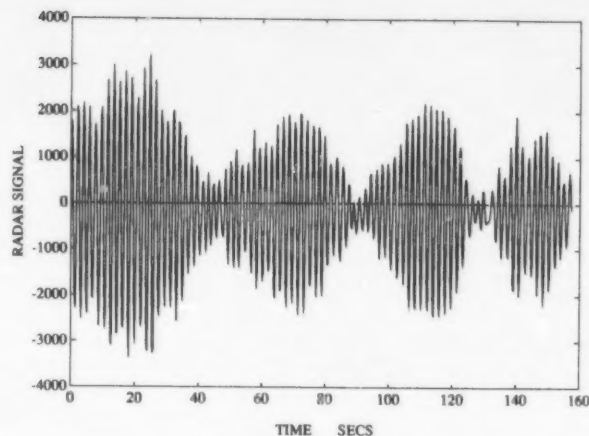


Fig. 2. Observed amplitude variations of HF radar time series, ocean returns only.

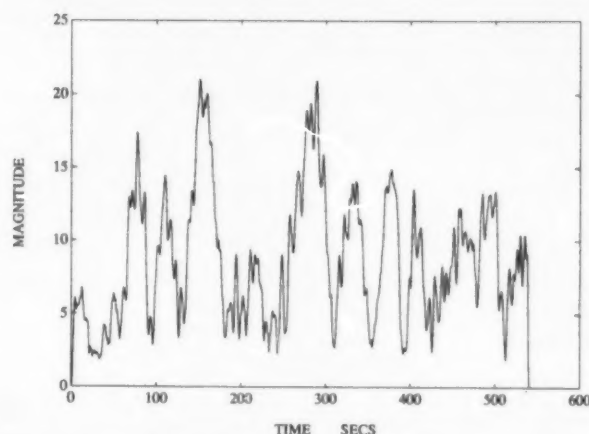


Fig. 3. Magnitude fluctuations of ocean-clutter component corresponding to the approaching of "Bragg" waves.

wave-packet behavior; i.e., the energy at these frequencies was arriving in packets with random amplitudes and random time separation. For example, Fig. 3 shows the time-varying magnitude fluctuations of the approaching Bragg. It was also established that the phases of the individual wave packets showed no relationship with each other.

The above investigation did not lead to a useable model for the ocean clutter. Complex demodulation at frequencies significantly separated from the Bragg frequency also exhibited a similar behavior. This, coupled with the fact that the clutter signal could not be adequately modeled with a reasonable order prediction filter, led us to investigate the possibility that the dominant components of the ocean clutter may have a time-varying frequency characteristic.

III. TIME-VARYING CHARACTERISTICS OF HF OCEAN CLUTTER

This section describes the results of our study of the time-varying frequency characteristics of HF radar ocean-clutter signals. The need to estimate signal parameters over short data segments prompted us to apply parametric and adaptive methods to these signals. Specifically, simple estimation algorithms, based on the well-known technique of linear prediction, were used to

establish the following characteristics of ocean clutter signals:

a) In a short time frame, the clutter signals consist essentially of two narrow-band Doppler signals only, corresponding to the two Bragg-scattering frequencies.

b) The frequencies of the two narrowband Doppler signals vary with time; their average values agree with the theoretically predicted Bragg-Doppler frequencies.

c) A low-order prediction filter, with time-varying coefficients, adequately models both the first- and second-order Doppler spectra.

According to existing theories, the ocean-clutter signal is stationary and no time-varying behavior is predicted. The results of this section, however, suggest that when observed during periods much shorter than a minute, the ocean-clutter signals are strictly nonstationary. It follows that optimal processing of HF radar data cannot be achieved with time-invariant techniques.

A. Linear Prediction Model

It is well known that, at high signal-to-noise (SNR) ratios, linear prediction (LP), or autoregression (AR) based methods can be effectively used to estimate the parameters of sinusoidal signals. The basis of the AR parametric model of a signal is that its value $\tilde{x}(k)$, at any time instant, can be predicted as a weighted sum of L previous values [10]:

$$\tilde{x}(k) = - \sum_{i=1}^L x(k-i) \cdot a_i. \quad (1)$$

Here, L is the order of the prediction filter, and a_i are the prediction coefficients. A prediction-error filter (PEF) performs the operation of subtracting the predicted signal value from the actual signal value. It is important to note that, if the signal fits this parametric model, then the output of the PEF is white. The "whiteness" of the PEF output is thus a simple and effective measure of the performance of the prediction model; this measure was used to evaluate the confidence level of our model parameter estimates.

The PEF is an all-zero filter, and it can be shown that, for a signal containing M sinusoids, the transfer function of the PEF has M zeros on the unit circle at the angular locations corresponding to the angular frequencies of the M sinusoids in the signal [11]. It can also be shown that if the PEF has L zeros, where $L > M$, then the $L-M$ extraneous zeros are uniformly distributed in angle around the inside of the unit circle. These properties of the PEF can be used to test the hypothesis that the ocean-clutter signal contains only two narrow-band sinusoids with time-varying frequencies near the Bragg frequency. During a short time frame, the number of zeros of the PEF on the unit circle determines the number of sinusoids in the signal, and their angular positions determine the frequencies of the sinusoids.

To track the proposed time-varying behavior of the ocean-clutter signal, the coefficients of the PEF must be estimated using very short data segments; alternately, an adaptive scheme may be implemented to continuously update their values. Both these approaches were used and gave very similar results.

The first scheme was implemented based on the forward-backward linear prediction (FBLP) method [12], [13]. This is a robust technique which estimates the PEF coefficients by minimizing the prediction errors both in the forward and backward directions. For a signal vector $x(k)$, $k = 1, 2, \dots, N$, and a prediction order L , the prediction coefficients a_i may be esti-

mated by solving the following system of linear equations:

$$\begin{bmatrix} x(L) & x(L-1) & \cdots & x(1) \\ x(L+1) & x(L) & \cdots & x(2) \\ \vdots & \vdots & \ddots & \vdots \\ x(N-1) & x(N-2) & \cdots & x(N-L) \\ x^*(2) & x^*(3) & \cdots & x^*(L+1) \\ \vdots & \vdots & \ddots & \vdots \\ x^*(N-L+1) & x^*(N-L+2) & \cdots & x^*(N) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_L \end{bmatrix} = - \begin{bmatrix} x(L+1) \\ x(L+2) \\ \vdots \\ x(N) \\ x^*(1) \\ \vdots \\ x^*(N-L) \end{bmatrix}. \quad (2)$$

This system of equations is generally over-determined and typically a least-squared solution is attempted. When these prediction coefficients are used in a PEF, the transfer function can be directly written as:

$$H(z) = 1 + \sum_{i=1}^L a_i z^{-i}. \quad (3)$$

As mentioned above, the zeros of $H(z)$ lying at or very close to the unit circle determine the number of sinusoids present in the signal.

The technique of linear prediction can be easily implemented to operate in an adaptive mode. Fig. 4 shows the block diagram of an adaptive PEF. The adaptive filter attempts to minimize the error between the input signal and filter response from a single sample-delayed version of the input; the filter adapts towards a prediction filter. This scheme was implemented using the sub-routine SPNLMS [14], which is based on the well-known LMS algorithm [15]. The filter coefficients $a_i(k)$ are updated, for each input sample, according to the following:

$$A(k+1) = A(k) + \frac{2 \cdot \mu \cdot e(k) \cdot X(k)}{(L+1) \cdot [\sigma(k)]^2} \quad (4)$$

$$[\sigma(k)]^2 = \alpha \cdot [x(k)]^2 + (1-\alpha) \cdot [\sigma(k-1)]^2$$

where

$$A(k) = [a_1(k) \ a_2(k) \ \cdots \ a_L(k)]^T$$

$$X(k) = [x(k) \ x(k-1) \ \cdots \ x(k-L)]^T$$

$$0 < \mu < 1$$

$$0 < \alpha \ll 1.$$

The adaptation performance of the algorithm is controlled by the two parameters μ and α . The first parameter μ is called the convergence parameter, which must be matched to the signal statistics. If μ is too large, the filter coefficients change rapidly to compensate for instantaneous errors, but convergence to the true value may be very slow. Conversely, if μ is too small, the system may not react rapidly enough to cope with changing signal statistics. The parameter α is referred to as a "forgetting"

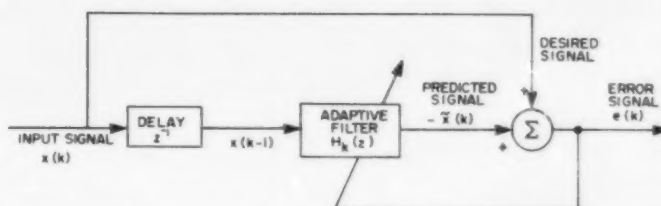


Fig. 4. Block diagram of an adaptive filter operating in the prediction mode.

factor and enables operation in nonstationary environments. As seen in (3), updating the variable α is done in such a manner that the past values of $x(k)$ are weighted exponentially and their effect becomes negligible after a time period corresponding to approximately $1/\alpha$ samples.

B. Experimental System

The experiments were performed using a CODAR (Coastal Ocean Dynamics Applications Radar) system. This is a 25.4-MHz radar system originally designed to measure ocean-surface currents; it has been modified here to enable operation with a narrow-beam receive antenna. The wide-beam transmit antenna consisted of a 3-element Yagi array, and the receive antenna was a 12-element, quarter-wave monopole array with a 9.45-m spacing; this corresponds to a receive beam-width of 6° about the fixed look direction of the radar beam.

The radar data analyzed in this paper was collected during an ice-detection experiment performed at Lumsden Beach, Bonavista Bay, in Spring 1989. Fig. 5 shows the location of the radar receive antenna and indicates the dimensions of an ocean range cell; i.e., the size of the ocean patch from which radar data is collected as a time series. This experiment was part of a project to develop a remote sensor of ice hazards from floating platforms. A reliable detection of ice hazards, beyond the line-of-sight of microwave sensors, is a major concern for the offshore resource-development industry. The main objectives of the Lumsden Beach experiment was to verify the analytical predictions of iceberg returns for HF radar and to test target-detection and tracking techniques. The data collection was primarily aimed at smaller ice masses, such as "growlers" and "berg bits," for which experimental data are not available in the HF band.

C. Frequencies in the Ocean-Clutter Signal

The first objective was the determination of the number of sinusoids contained in the ocean-clutter signal. If the frequencies of these sinusoids vary with time, then the prediction coefficients for this signal would also exhibit a time variation. Thus, using the adaptive PEF described above, the roots of the PEF transfer function were evaluated at every iteration to determine the locations of the zeros. Using HF radar data from an ocean cell, at a range of 6 km, Fig. 6 is a cluster plot of 425 sets of PEF transfer function zeros computed at time intervals of 0.262144 s. The length of the prediction filter used was three, and it is seen that only two zeros are clustered near the unit circle. The angular location of the cluster centers correspond to the two theoretically predicted Bragg frequencies. The location of the third cluster, well within the unit circle, denies the existence of a third sinusoid [11].

As a further test, Fig. 7 was obtained using a PEF of length 9. Again, it is seen that only two roots cluster on the unit circle, confirming that the signal contains two sinusoids only. Note that

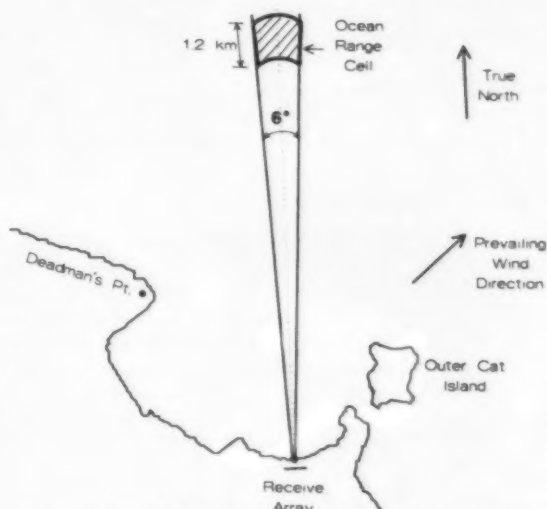


Fig. 5. Location of the HF radar system during the ice detection experiment at Lumsden Beach, Bonavista Bay. The geometry of the ocean range cell is determined by the 1.2-km range resolution and the 6° beamwidth of the system.

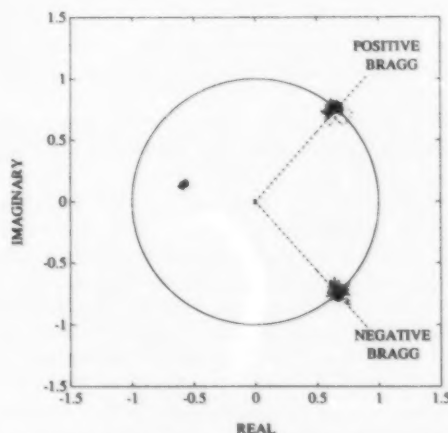


Fig. 6. Cluster plot of adaptive PEF transfer function zeros. The input to the filter was HF radar data with ocean-clutter signal only. Filter length = 3; $\mu = 0.06$; and $\alpha = 0.04$.

the remaining seven roots also cluster, uniformly distributed in angle, on a single circle. This behavior of the extraneous roots is a characteristic of a higher order PEF [11]; the radius (< 1) of the circle on which they lie cannot be easily related to any of the signal parameters.

Both Figs. 6 and 7 show a significant spread, in the angular position, of the two roots clustered on the unit circle. The spread in angular position is directly related to the frequency variations

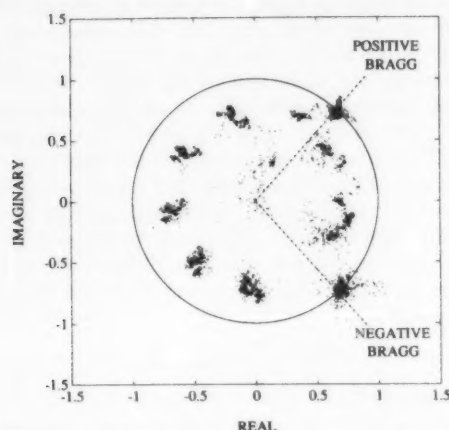


Fig. 7. Root cluster plot, similar to Fig. 6, corresponding to a higher order adaptive PEF. Only two roots cluster on the unit circle, indicating a signal with two sinusoids. Filter length = 9; $\mu = 0.04$; and $\alpha = 0.04$.

of the corresponding sinusoids. Similar cluster plots have been obtained using a number of different HF radar data sets. These tests led to the conclusion that the ocean-clutter signal contains two narrowband sinusoids, with time-varying frequencies, centered around the theoretically predicted Bragg frequencies.

Referring to Fig. 4, the signal $\hat{x}(k)$ is effectively a modeled version of the input signal based on a time-varying prediction filter of order L . Fig. 8 demonstrates the close correspondence between $\hat{x}(k)$ and $x(k)$ using an adaptive prediction filter of length 3. The performance of this modeling can be judged more easily by comparing the spectra of the input and modeled signals, as shown in Fig. 9. The spectrum of the modeled signal in Fig. 9(b) clearly reproduces the main characteristics of the input spectrum; the well-known first- and second-order Doppler clutter components have been accurately modeled. It must be noted that no significant effort has yet been made to optimize the parameters of the adaption algorithm which may improve the modeling performance.

D. Time-Varying Behavior of Bragg Frequencies

There is a direct correspondence between the angular position of the zeros of the PEF transfer function and the frequency of the sinusoid contained in the signal. Thus by analyzing the zero locations at each iteration, the time variations of the sinusoids in the clutter signal could be established. For this test, the least-squares estimation of the prediction coefficients was used. Two prediction coefficients were estimated using a 15 sample data window corresponding to a 3.9-s time period. The locations of the PEF zeros as well as the frequencies of the two sinusoids could then be computed at time intervals corresponding to the sample interval of the clutter signal. Using the same data as in the previous subsection, Fig. 10 shows the estimated time variations of the frequencies of the ocean-clutter signal.

We believe that these observed frequency variations of the ocean-clutter signal may contain answers to a number of questions regarding the interaction of HF radar with ocean waves and may provide insight into the fundamental behavior of ocean waves. The first obvious interpretation of Fig. 10 is simply that the 5.9 ocean waves, corresponding to the Bragg frequency, are not moving with a constant velocity. Rather, possibly due to interaction with other ocean waves, their velocity is constantly changing about an average velocity. It can be easily shown that this velocity variation would cause an angle modulation of the

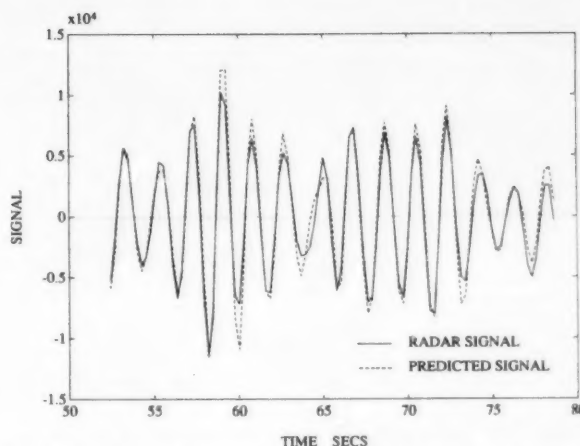


Fig. 8. Comparison of true and predicted values for an adaptive prediction filter of length 3, operating on the ocean-clutter signal.

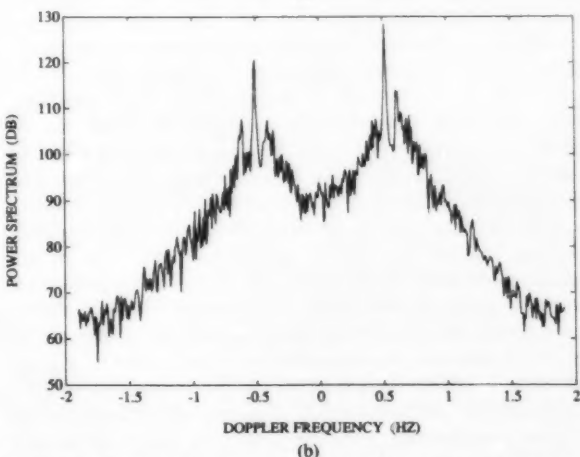
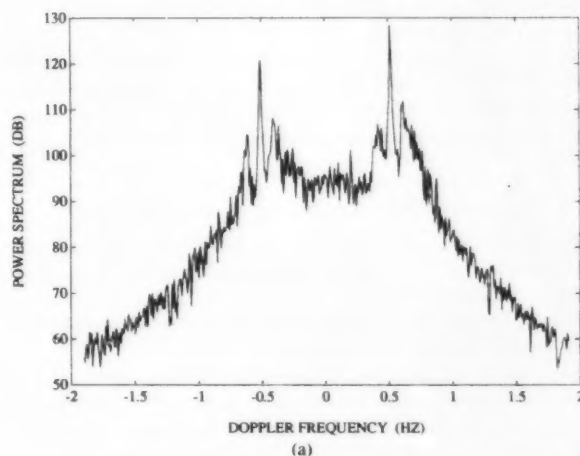


Fig. 9. Comparison of the spectra of the signals in Fig. 8: (a) Spectrum of ocean clutter signal. (b) Spectrum of modeled ocean clutter at the output of prediction filter.

radar Doppler return, causing the observed frequency variations. Based on this interpretation, a composite description of the ocean surface obtained using HF radars operating at different wavelengths could enhance our understanding of the ocean waves.

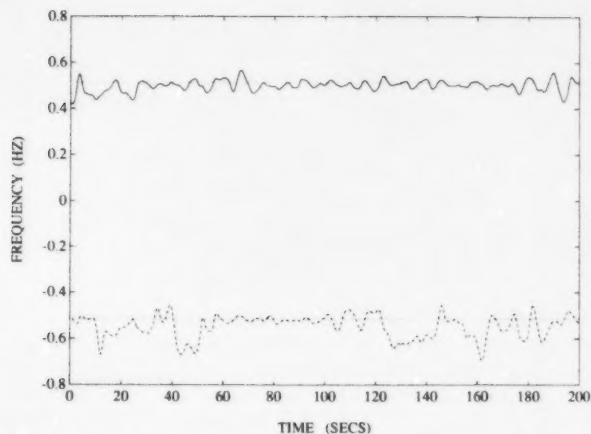


Fig. 10. Time-varying behavior of the two dominant narrowband frequency components in HF radar ocean clutter.

To reiterate, these results indicate that HF radars sample some time-varying characteristic over a limited area of the ocean surface. It is postulated that this time-varying behavior is related to the ocean wave-height spectrum. However, further studies are needed to link our results with existing theories of ocean waves and their interaction with the electromagnetic waves transmitted by HF radar.

IV. CLUTTER SUPPRESSION FOR TARGET DETECTION

The results of the previous section clearly show that the main characteristics of the ocean-clutter signal can be easily modeled using a low-order adaptive predictive filter. In this section a simple technique is presented to increase the signal-to-clutter ratio for HF returns from a target.

The data to be analyzed contained an iceberg target with a water line area of about 155 m². The range to the iceberg was 8.4 km and, as the iceberg was moving across the radar bore-sight, had a very low radial Doppler velocity component. Assuming two sinusoidal components for the ocean clutter, the radar signal now contains an additional third signal component. As a first attempt at clutter suppression, the scheme illustrated in Fig. 11 was used. We want to design an adaptive prediction filter for the clutter components of the signal only. This may be achieved by first applying a bandpass filter to the input signal to isolate the clutter components. In this example an extremely simple two-pole bandpass filter was used; at the Bragg frequencies the maximum gain of the filter was 16.6. This bandpass signal was input to an adaptive prediction filter. Due to the bandpass suppression of the target signal, it did not contribute appreciably to the prediction-filter coefficients. In other words, the prediction filter was designed to model the clutter signal only. When the same prediction filter was applied to the original radar data, it effectively cancelled out the clutter components and did not affect the target signal. The resulting enhancement of the signal-to-clutter ratio is clearly seen in the following figures: Fig. 12(a) shows the real part of the raw radar input signal. The output, after processing by an adaptive prediction filter of length 3 as shown in Fig. 12(b), demonstrates that the clutter components have been suppressed and the extremely low-frequency Doppler signal from the iceberg is clearly visible. Fig. 13(a) and (b) are the spectra of the input and processed signals, respectively. It should be noted that, for simplicity, these spectra were obtained by simple fast Fourier transform operations and no

attempts were made to improve the spectral estimates through windowing or other techniques. The first-order ocean-clutter signals near ± 0.5 Hz have been suppressed by about 40 dB.

It is expected that extensions of this simple technique presented here could result in robust and reliable methods for low Doppler target detection using HF radar. For example, the statistics of the clutter-frequency variations could be estimated using a number of neighboring range cells. This could allow the influence of the target signal in updating the adaptive filter coefficients to be minimized. This would be specially critical in situations where the Doppler frequency of the target signal falls close to the dominant Bragg frequencies. Work on this aspect is progressing and will be reported soon.

V. ESTIMATION OF THE OCEAN WAVE SPECTRUM

It is postulated that the time variations of the Bragg frequencies, as shown in Fig. 10, are related to velocity variations of the 5.9-m ocean waves responsible for the Bragg scattering. Then it can be argued that these velocity variations are caused by the 5.9-m ocean waves interacting with ocean waves of other wavelengths. In other words, it is suggested that the spectrum of these velocity variations is related to the ocean wave-height spectrum. Thus, the observed frequency variations of the ocean-clutter signal should contain information about the ocean wave-height spectrum.

From a different point of view, the HF electromagnetic waves interact selectively with a particular ocean wavelength. If the instantaneous velocity of this specific ocean wave is related to the ocean conditions, then the instantaneously observed Doppler frequency should also be related to the ocean conditions.

According to well-known ocean wave theory, the propagation velocity v of the waves is directly related to their wavelength L [16]:

$$v = \left[\frac{g \cdot L}{2 \cdot \pi} \right]^{1/2} \quad (5)$$

Thus the 5.9-m ocean waves are traveling with a velocity of about 3.04 m/s. These waves are being constantly overtaken by waves of longer wavelengths, and are themselves constantly overtaking waves of shorter wavelengths. Thus, from an intuitive point of view, although the waves may exhibit an average velocity as given by (5), interaction with other waves should result in velocity perturbations. Further, these velocity perturbations should be related to the sea state. A simple relationship may therefore exist between the frequency variations of the Bragg-Doppler returns and the ocean wave-height spectrum. In fact, for a narrow-beam radar, one may be able to estimate the two-directional wave-height spectra looking away and towards the radar site.

To test the above reasoning, the spectra of the Bragg-frequency variations were averaged over three neighboring radar range cells. One result is shown in Fig. 14, where the individual spectra were estimated over about 67-s time windows and were normalized before averaging. This particular data corresponds to a range of 6 km, and the time variations of the Bragg frequency, for a single-range cell, were shown in Fig. 10. One feature of this estimated spectrum appears to correspond to the wave-height spectrum when compared with a superimposed theoretical Pierson-Moskowitz ocean wave-height spectrum $e(f)$, computed according to [17]:

$$e(f) = 2\pi C_p g^2 \omega^{-5} \exp \left[-0.74(g/\omega U)^4 \right] \quad (6)$$

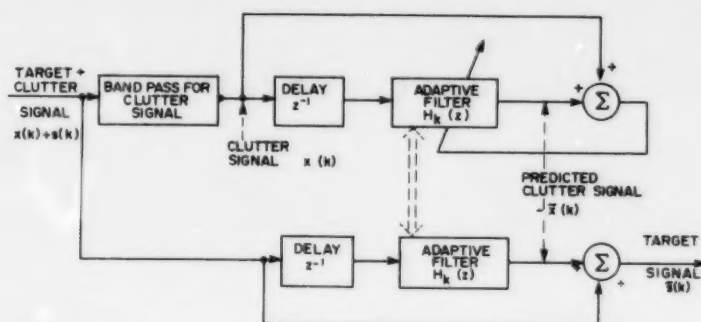


Fig. 11. Signal-to-clutter ratio enhancement using an adaptive prediction filter.

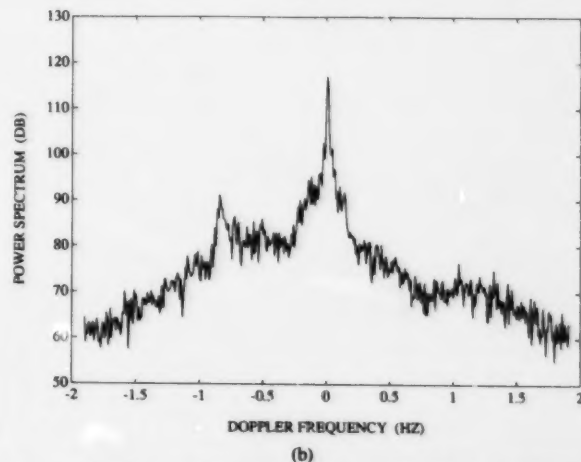
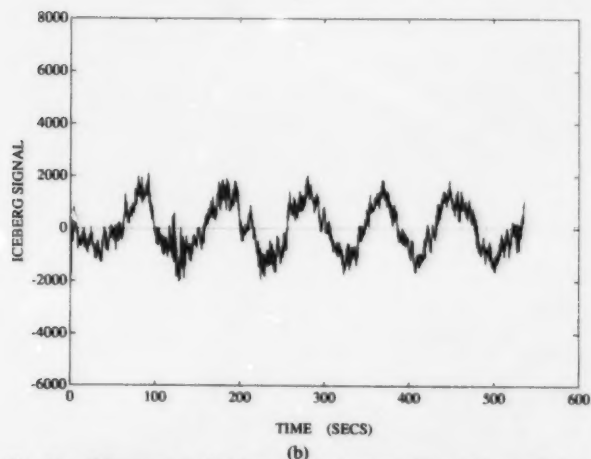
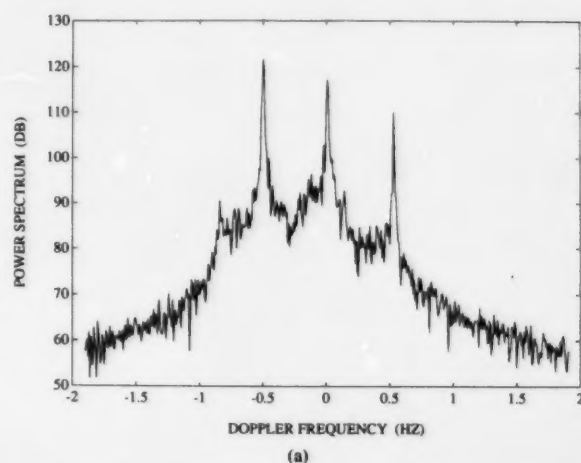
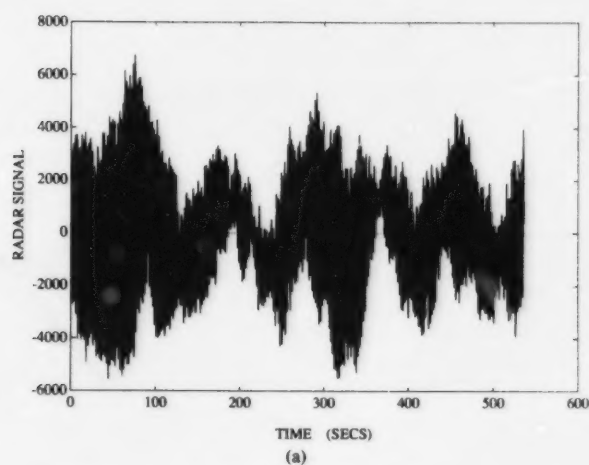


Fig. 12. Enhancement of iceberg target signal using the scheme in Fig. 11, filter length 3: (a) HF radar signal with iceberg target. (b) Iceberg signal after clutter suppression.

Fig. 13. Comparison of the spectra of the signals in Fig. 12: (a) Spectrum of iceberg and clutter. (b) Enhanced spectrum after clutter suppression.

where the constant $C_p = 1.09$; g is the acceleration of gravity; ω is the radium frequency; and $U = 14$ m/s is the wind speed.

The constants U and C_p were adjusted to fit the peak of the estimated spectrum. The other lower frequency peak in the estimated spectrum is not presently explicable. It must be pointed out that ocean condition data were not available and no measure of the reliability of this estimate is possible.

We are currently proceeding HF radar data from an experi-

ment in which wave-buoy data were collected to test the wave-height spectrum estimates from this proposed technique.

Presently available techniques for ocean wave-height spectrum estimation from HF radar data involve inversion procedures which are susceptible to numerical instabilities, particularly for low levels of signal-to-noise ratios. In contrast, the technique being investigated here is based on direct estimation of signal parameters and is thus expected to be inherently stable.

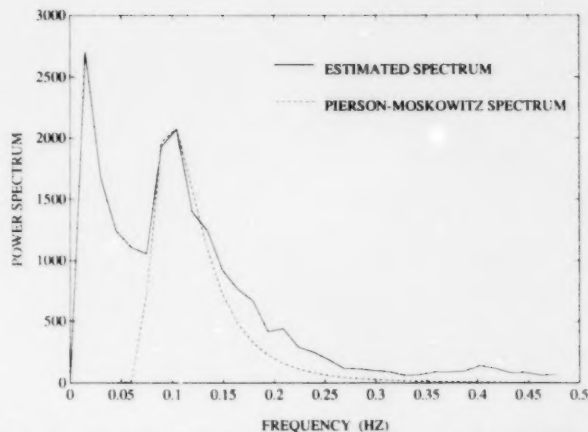


Fig. 14. Ocean wave-height spectrum estimated under the assumption of a relationship between the time variations of the Bragg clutter frequencies and the ocean surface.

VI. CONCLUSIONS

A few fundamental time-domain characteristics of HF radar ocean-clutter signals have been established. Specifically, it is shown that the ocean clutter may be adequately modeled with two narrowband Bragg signals with time-varying frequencies. Low-order adaptive-prediction filters can thus be used to suppress the ocean clutter. Simple adaptive filters can also be designed to improve the signal-to-clutter ratio for low Doppler target signals.

It is postulated that the time variations of the Bragg frequencies are related to the ocean wave-height spectrum. Initial results along these lines suggest that this may lead to an alternate, more robust, method of estimating the sea state from HF radar data.

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